

Synchronizing phasor measurement and STATCOM controller in power system stability enhancement

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ABSTRACT

The objective of this paper is to present the concepts of synchronizing phasor measurement (SPM) and its strategic application in addition with a STATCOM controller for augmentation of dynamic stability in a multi-machine power network. The bus voltages of the power network under consideration are estimated in the form of digital signal by a synchronizing phasor measurement unit (SPMU). The output of the PMU is then applied to a fixed structure PI type lead-lag digital STATCOM controller in order to study the performance of this discrete-time digital control in comparison to its analog counterpart for the present control problem. The parameters of the analog controller are first tuned with a popular soft computation technique, particle swarm optimization (PSO) and later this controller is converted to digital one for simulation with sampled data outputs received from SPMU. The validation and effectiveness of the design of the proposed control scheme is illustrated through time domain simulation of a proposed 3-machine, 9-bus test power system. The simulation results of the machine speed deviation response established that the SPM based digital control system is more effectual and resulting better performance than the continuous-time analog control system in power system stability improvement.

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1. INTRODUCTION

The problem of small signal stability in power systems is a long standing issue to the researchers. Power system stabilizers (PSSs) [1] are widely used in power industries to maintain the stable operation of power systems following small and large disturbances. With ever growing changes in global economic scenario, the demand of power generation and the stress over the power networks are rising increasingly. Therefore, the uses of the modern controlling devices, FACTS [2-4] are remarkably taken into account, because of its reliable, fast and economic operation. Static synchronous compensator (STATCOM) is an important member in the FACTS groups that are evident to be robust and effectual to mitigate operational difficulties in power networks [5-7].

It is well established that the constraints of analog controllers can be get rid of by utilizing digital signal processing (DSP) based controllers whose operations are programmable, precise and can be easily upgraded by employing high speed, sophisticated hardware. A number of investigations on digital control schemes for power system operations and control are reported in the literature [8, 9]. The concepts of DSP based measurement of voltage and current phasor are introduced in early eighties [10, 11]. After that it is

increasingly used by the researchers. In modern smart grid scenario digital signal processing based phasor measurement technology plays a key role in power system monitoring, control and protection [12-14].

The problem of design of any controller is the complication of its right tuning. The tuning required prior knowledge of the operational behaviour of the system. It has also inherent cost of solving difficulties and burden. Some global search evolutionary algorithms such as fuzzy logic control, genetic algorithm (GA) based fuzzy control, artificial neural network (ANN), particle swarm optimization (PSO) etc. have been utilized to design and investigate many power system optimization problems [15-17]. Among these techniques, PSO is being increasingly used by the researchers recently [18, 19]. PSO bears robustness and stability property and also has speedy convergence profile than other available techniques of optimizations. The benefits of PSO compared to GA are that the 'crossover' and 'mutation' operations are not required in PSO.

The huge expansion of power networks and its complexity impel the power system researchers towards the great challenge in terms of grid stability, security and safety, which introduces the concept of wide area monitoring (WAM) and control. In WAM systems it is possible to operate and control the grid satisfactory to save power systems from major blackout. SCADA systems are suitable only for local monitoring and control in a power network with high data latency. However, synchronizing phasor measurement unit (SPMU) is one of the important equipment for WAM and control of power systems with high degree potential and accuracy. It is a sophisticated monitoring device that can measure the instantaneous voltage, current and frequency at any specific locations on the grid and gives real-time data of the system which allows making decisions to prevent power outage and severe blackout.

Several investigations have been carried out by the power system researchers in this direction. The application of PMU for wide area monitoring and control system has been shown in [20]. The location of PMU in a grid is another important aspect. Many researchers have focused their work on optimal placement of PMU. The [21] presents a non-linear programming-based model for the optimal placement of phasor measurement units based on full system observability and to maximize the measurement redundancy at all buses in a power system. Taxonomy for optimal placement of phasor measurement unit has been reported in [22]. This paper offers a unifying description of a relatively large number of works devoted in this issue. Attempts also have been made to apply heuristic optimization method. In [23] a recursive Tabu search method has been employed in finding optimal location of PMU. The method of binary particle swarm optimization has been applied in [24] in order to find optimal PMU location for power system observability considering measurement redundancy.

In view of the above importance in critical service of PMU author has motivated to expedite the work on application of synchrophasor and its related aspects. In this paper author has shown the strategic application of SPMU and digital STATCOM controller for the purpose of mitigating transient stability problem in a multimachine power network. A heuristic optimization method PSO has been implemented to get the optimal values of the variables of a PI type lead-lag STATCOM controller. This analog controller is converted to digital one (z-domain) via Tustin's transformation to adopt digital signal generated from phasor measurement unit. The voltage phasor of local substations are considered to be measured by the PMU. The DSP based outputs of the PMU are then employed to the discrete-time STATCOM controller. It has also been assumed that the communication between the STATCOM controller and the SPMU are based on global positioning systems (GPS) technology via wide area communication network (WAN). As far as author's knowledge is concerned the proposed scheme of application digital control in association with phasor measurement strategy has not been addressed so far in the existing literatures.

The content of the paper is oriented as follows: In section 2 the concepts of synchronizing phasor measurement and the PMU has been described. The construction of conventional STATCOM controller via PSO in association with multimachine modelling and the configuration of digital controller have been demonstrated in section 3. Finally, act and effectiveness of the suggested DSP based control with respect to the continuous-time analog control has been looked over in section 4 and conclusions are drawn in the last section.

2. SYNCHRONIZING PHASOR MEASUREMENT

2.1. Phasor measurement concepts

A phasor is a unique complex quantity, used to represent graphically a pure sinusoidal waveform. A pure sinusoidal signal can be represented by (1).

$$X(t) = X_{max} \cos(\omega t + \varphi) \quad (1)$$

The phasor of (1) can be written as:

$$X(t) = \frac{X_{max}}{\sqrt{2}} e^{j\phi} \quad (2)$$

In order to measure the quantity as a bus voltage the (2) can be written as:

$$V(t) = \frac{|V_{max}|}{\sqrt{2}} e^{j\phi} \quad (3)$$

A continuous or constant phasor means a persistent waveform but the signals under investigation are not practically remain persistent, their frequency also variable and may contain harmonic or non-harmonic components. The task of a PMU is to extract the fundamental part and computes its phasor over a finite data set in one period of the fundamental frequency of the input signal. The commonly employed method for estimation of phasor is the utilization of the sampled data input signal, and the application of discrete fourier transform (DFT) on it. If $V(n)$ $\{n = 0, 1, 2, \dots, N-1\}$ are the N samples of the input signal $V(t)$ at $t = n\tau$, where τ is the sampling interval taken over 1 period of the normal frequency of the power system, then the phasor representation is given by [25].

$$V_k = \frac{1}{\sqrt{2}} \frac{2}{N} \sum_{n=0}^{N-1} V(n) e^{-j \frac{2\pi kn}{N}} \text{ for } k = 0, 1, 2, \dots, N-1 \quad (4)$$

Where V_k is the phasor and the sampling angle, $\theta = 2\pi/N = 2\pi f_0 \tau$ for sampling interval τ with nominal power system frequency f_0 . Note the frequency ω appear in the DFT at $\pm \omega$ can be combined, which introduces a factor 2 in front of the summation. The (4) is the phasor representation of the voltage input signal estimated by the DFT in one period of data window. It is worthwhile to mention that the PMU generally produces standard outputs with positive sequence phasors.

Assuming, $t = 0$ is the time at which the measurement is being started, see Figure 1, the PMU computes the phasor as given by (4) utilizing the digital data of the input signal. The (4) represents a non-recursive phasor measurement in a one period of fixed-length data window. It is to be noted that each time a new phasor is generated when a new sample is acquired in a data window. The continuous monitoring of this data can be handled efficiently through recursive algorithm. In recursive form the computation of phasor for each data window is done by repeating the (4) in identical fashion. Let V_k represents the phasor for the sampled data set $V(n)$ $\{n = k, k+1, \dots, N+k-1\}$, let a new measurement is taken to generate a new set of data $V(n)$ $\{n = k+1, k+2, \dots, N+k\}$. Therefore, the phasor for the new data window can be computed as:

$$V_{k+1} = V_k + \frac{\sqrt{2}}{N} [V(N+k) - V(k)] e^{-jk \frac{2\pi}{N}} \quad (5)$$

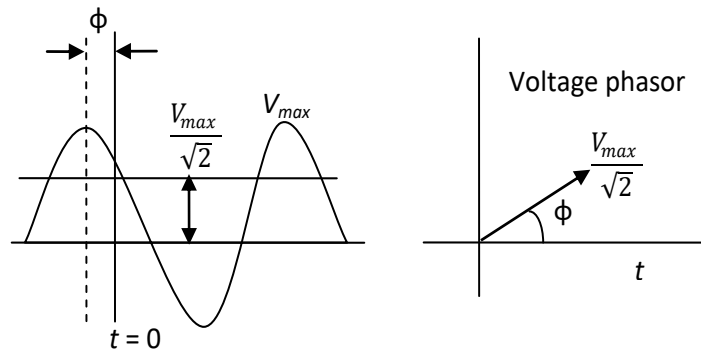


Figure 1. Voltage signal and its phasor diagram

It is evident that the recursive formulation (5) is simple and it involves computation of only two samples: $V(N+k)$ and $V(k)$ but in the non-recursive formulation (4) computations are performed with N

samples. A practical sampling rate around 16 times ($f_s = 16f_0$), of the standard power system frequency, $f_0 = 50\text{Hz}$ gives sampling frequency $f_s = 800\text{Hz}$, which generates $N=16$ samples in one period of the input signal. In Radix-2, fast Fourier transformation (FFT) algorithm requires ($N = 16 = 2^4$) 4-stages of butterfly computation. It is possible to perform this task online with the help of digital signal processor (DSP). It is customary to mention that in a smart substation, all measurement signals will be time synchronized with high accuracy via GPS signal. The estimation of the substation parameters are considered to be achieved through synchronized phasor measurement (SPM) technology. Therefore, it is feasible to represent the phasors of all remote signals in a same phasor diagram by synchronization of their sampling process. Thus, monitoring and control of wide area signals can be possible with this technology with high fidelity from remote control centre as shown in Figure 2.

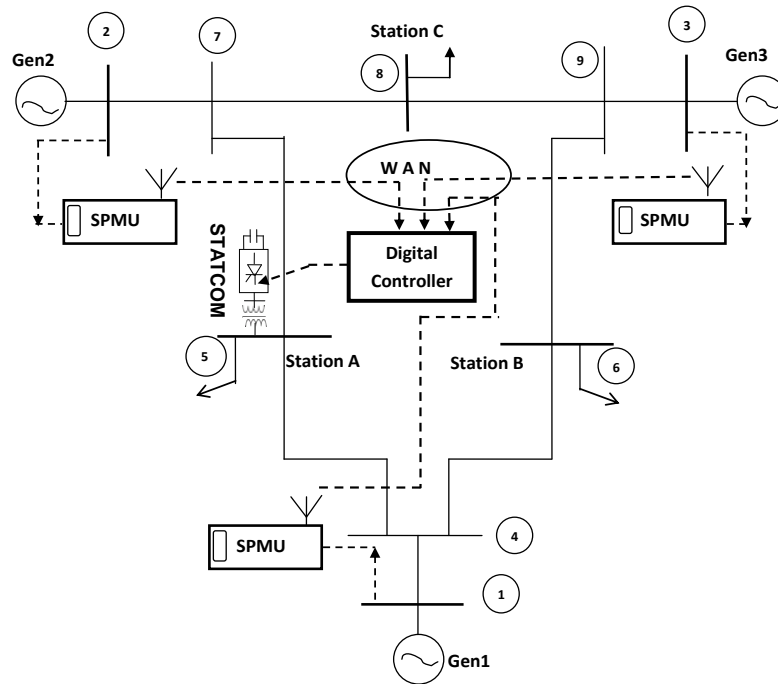


Figure 2. Application of SPMU in wide area application

2.2. Synchronizing phasor measurement unit (SPMU)

The functional blocks for a typical SPMU are demonstrated in Figure 3. The SPMU uses time synchronizing measured variables from GPS system. The acquired GPS wave is transformed to an acceptable intermediate frequency (IF) in the front end GPS receiver, and then refined by the phasor microprocessor. The power station GPS receiver is assumed to be located at point X, where three spheres with radii R_1 , R_2 , R_3 intersect as shown in Figure 4.

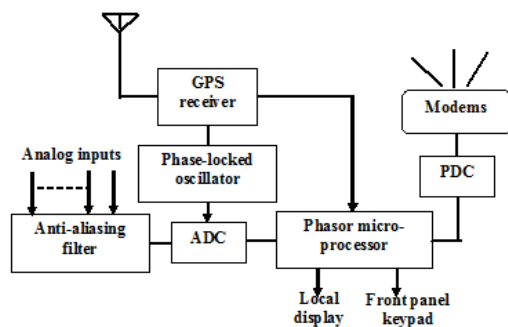


Figure 3. Synchronizing phasor measurement unit (SPMU)

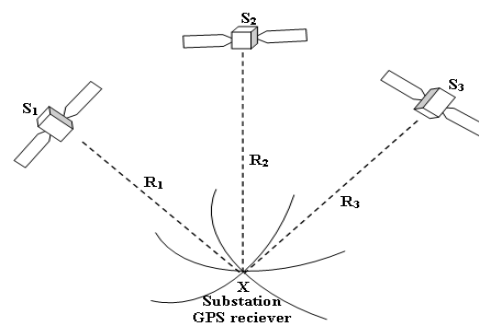


Figure 4. Substation GPS measurement

The GPS receiver generates the 1 pulse-per-second (pps) signal and a time tag, which may consists of the year, day, hour, minute, and second. The 1-pps signal is converted into the required number of pulses with a phase-locked oscillator for sampling of the analog input. The microcontroller computes the positive sequence phasors using the recursive algorithm (5). The computed string of phasors, one for each of the positive sequence measurements, is assembled in a phasor data concentrator (PDC) and this phasor data stream from PDC is then transmitted through a dedicated communication network at a rate of about every 2-5 cycles (40-100 msec) of the fundamental power system frequency (50 Hz). As the power system dynamic problems are usually initiated in the low frequency range (0.2-2.5 Hz), therefore it is possible to study in real-time the problem of dynamic instability reliably at the control point.

3. DESIGN OF ANALOG AND DIGITAL STATCOM CONTROLLER

3.1. Prototype schematic of STATCOM controller

The STATCOM controller prototype as a voltage controller is sketched in the Figure 5 [26]. The STATCOM in conjunction with only a voltage control device is not sufficient to dampen every undamped modes of the whole system. Thus, it is usual practice to incorporate a supplementary control in addition with the STATCOM voltage regulator. As the generator speed captures the effect of every undamped mode, therefore, the speed deviation signal of the generator can be utilized as the supplementary control action signal for the STATCOM.

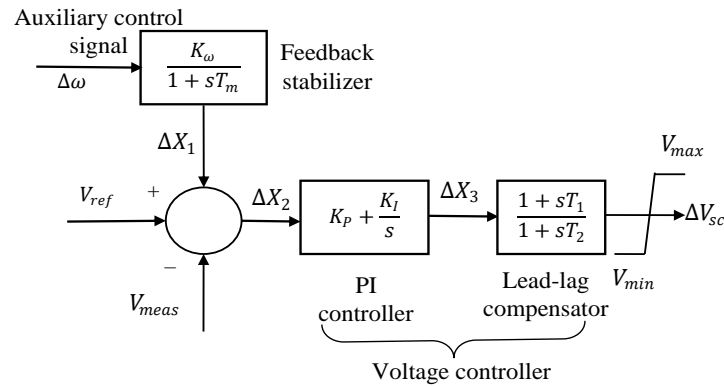


Figure 5. STATCOM voltage controller

The block-diagram of the STATCOM voltage controller, see Figure 5, can be written under mentioned state in (6-8):

$$\Delta \dot{X}_2 = -\frac{1}{T_m} \Delta X_2 + \frac{K_\omega}{T_m} \Delta \omega - \frac{1}{T_m} \Delta V_{meas} \quad (6)$$

$$\Delta \dot{X}_3 = \left(-\frac{K_p}{T_m} + K_i \right) \Delta X_2 + \frac{K_p K_\omega}{T_m} \Delta \omega - \frac{K_p}{T_m} \Delta V_{meas} \quad (7)$$

$$\Delta \dot{V}_{sc} = -\frac{1}{T_2} \Delta V_{sc} + \frac{1}{T_2} \Delta X_3 + \frac{T_1}{T_2} \left(-\frac{K_p}{T_m} + K_i \right) \Delta X_2 + \frac{T_1 K_p K_\omega}{T_2 T_m} \Delta \omega - \frac{T_1 K_p}{T_2 T_m} \Delta V_{meas} \quad (8)$$

3.2. Installation of STATCOM for a multigenerator power system

The two-axis linearized model of a multigenerator power network connecting basic power system components respectively exciter and power transmission networks have been described in [27]. This model can be presented as:

$$\Delta \dot{X} = A_1 \Delta X + B_1 \Delta I_g + B_2 \Delta V_g + E_1 \Delta U \quad (9)$$

$$0 = C_1 \Delta X + D_1 \Delta I_g + D_2 \Delta V_g \quad (10)$$

$$0 = C_2 \Delta X + D_3 \Delta I_g + D_4 \Delta V_g + D_5 \Delta V_l \quad (11)$$

$$0 = D_6 \Delta V_g + D_7 \Delta V_l \quad (12)$$

Here, (9) and (10) constitute the machine dynamic equations in linearized form and (11) and (12) depict the equations for the network correspond to the PV buses and the PQ buses respectively. The application of a STATCOM in the above system consequences insertion of state variables, $\Delta X_{Statcom} = [\Delta X_2 \ \Delta X_3 \ \Delta V_{sc}]^T$ with the machine DAE in (9-10) and the power flow equations of the STATCOM in the network equations (11)-(12). If it is assumed that the STATCOM is connected to any j -th load bus. The power flow equations of a STATCOM can be obtained as:

$$P_{sc} = |V_{sc}|^2 G_{sc} - |V_{sc}| |V_j| [G_{sc} \cos(\delta_{sc} - \theta_j) + B_{sc} \sin(\delta_{sc} - \theta_j)] \quad (13)$$

$$Q_{sc} = -|V_{sc}|^2 B_{sc} - |V_{sc}| |V_j| [G_{sc} \sin(\delta_{sc} - \theta_j) - B_{sc} \cos(\delta_{sc} - \theta_j)] \quad (14)$$

where, $V_{sc} \angle \delta_{sc}$ = STATCOM output voltage (ac) and $Y_{sc} = G_{sc} + jB_{sc}$. All symbols have their usual significances. Therefore, the active and reactive power flow equations corresponding to the load bus ' j ' in linearized form are given by (15). It has been further assumed that participation of the other load buses remain unchanged.

$$\begin{bmatrix} \Delta P_j \\ \Delta Q_j \\ \Delta P_{sc} \\ \Delta Q_{sc} \end{bmatrix} = \begin{bmatrix} \frac{\partial P_j}{\partial \theta_j} & \frac{\partial P_j}{\partial V_j} & \frac{\partial P_j}{\partial \delta_{sc}} & \frac{\partial P_j}{\partial V_{sc}} \\ \frac{\partial Q_j}{\partial \theta_j} & \frac{\partial Q_j}{\partial V_j} & \frac{\partial Q_j}{\partial \delta_{sc}} & \frac{\partial Q_j}{\partial V_{sc}} \\ \frac{\partial P_{sc}}{\partial \theta_j} & \frac{\partial P_{sc}}{\partial V_j} & \frac{\partial P_{sc}}{\partial \delta_{sc}} & \frac{\partial P_{sc}}{\partial V_{sc}} \\ \frac{\partial Q_{sc}}{\partial \theta_j} & \frac{\partial Q_{sc}}{\partial V_j} & \frac{\partial Q_{sc}}{\partial \delta_{sc}} & \frac{\partial Q_{sc}}{\partial V_{sc}} \end{bmatrix} \begin{bmatrix} \Delta \theta_j \\ \Delta V_j \\ \Delta \delta_{sc} \\ \Delta V_{sc} \end{bmatrix} \quad (15)$$

Therefore, for a power system network containing m machines and a STATCOM, the overall system matrix can be equated as:

$$[A_{Stat}]_{(7m+3) \times (7m+3)} = [A'] - [B'] [D']^{-1} [C'] \quad (16)$$

It is to be noted that the elements and dimensions of the sub matrices of (16) will be changed accordingly with the inclusion of the above dynamics of the STATCOM controller. In the successive stages this formulation has been deployed to work out swing modes and identification of critical swing mode in the PSO based optimization method. It is obvious from the Figure 5 that to construct the STATCOM controller there need four calibrated variables; gains for the PI controller (K_p, K_i), lead-lag block time constants (T_1, T_2). The feedback stabilizer constants K_w and T_m are fixed as 5.0 and 0.5 respectively. In the subsequent division these undecided parameters (K_p, K_i, T_1 and T_2) are optimized by virtue of PSO based approach with minimization of a predetermined cost function.

3.3. Overview of PSO

The PSO [28] is a heuristic optimization process inspired by the motion and mind of biological flock or school. It is started with a community of arbitrary outcomes and hunts for global optima by upgrading its originations. A 'swarm' comprises of " n " particles which are assumed to be moved in a D dimensional search room. Every particle in a swarm walks in the search room following up its velocity and direction at each step and eventually reached to the target which is corresponding to the best in its flight. This best particle in the community is denoted by (universal best, $gbest$) and the final position which has been visited by the best particle is designated by (local best, $pbest$). The PSO achieves the best suited solution by continuous revision of velocity of each particle in the direction of its universal best and local best position. The movement and location of the particles are evaluated by:

$$v_i(n) = \alpha * v_i(n-1) + a_1 * r_1 * (gbest_i - s_i(n-1)) + a_2 * r_2 * (pbest_i - s_i(n-1)) \quad (17)$$

$$s_i(n) = s_i(n-1) + v_i(n) \quad (18)$$

In (17) and (18) velocity of the particle i is designated by $v_i(n)$, which is usually considered as 10-20% of the acceptable span of the variables. $s_i(n)$ indicates the location of the i th particle. a_1, a_2 are two scalar coefficients that pull the entire particles towards the universal best and the local best position respectively and their values are generally set in the range $\in (0, 2)$. r_1 and r_2 are arbitrary variables with normal distribution with span $\in (0, 1)$. $\alpha \in (0, 1)$ stands for the inertia weight.

3.4. Strategy of PSO based optimization

In this section the strategy of PSO based optimization has been outlined. The problem is to find the best fit four unknown parameter (K_p, K_I, T_1 and T_2) of the STATCOM controller which has been accomplished through the minimization of a predefined target function defined as optimum damping index (ODI):

$$ODI = \eta = (1 - \beta_i) \quad (19)$$

In (19), β_i denotes the damping ratio of the i -th swing mode which is most vulnerable. The β and hence ' η ' can be calculated from the system matrix and eigenvalues of the multi-machine system with STATCOM controller. The (19) also illustrates the fact that minimization of the desired objective function, η can be possible though maximization of the damping ratio (β). Any alteration in the four tuning constants of the STATCOM controller, affects the β , which further changes the above cost function, ODI . The possible bounds for the parameters can be described as follows:

$$\text{Minimize } \eta \quad [\text{As in (19)}]$$

Subject to:

$$K_I^{min} \leq K_I \leq K_I^{max} ; K_p^{min} \leq K_p \leq K_p^{max} \quad T_1^{min} \leq T_1 \leq T_1^{max} ;$$

$$T_2^{min} \leq T_2 \leq T_2^{max}$$

3.5. Implementation of PSO method

This section implements PSO based optimization process using MATLAB toolbox, '*PSO toolbox*' [29]. In this toolbox '*pso_Trelea_vectorized.m*' is the main execution program which utilizes a bunch of sub-programs to run the complete optimization process. To evaluate the function (η) given in (19), the user created eigenvalue computation program has been called in the main program. In this problem the 'particle' has been customized through a vector comprising with four regulating parameters of the controller which can be represented by:

$$\text{Particle} = [K_p \quad K_I \quad T_1 \quad T_2] \quad (20)$$

The optimization process starts with random initialization of populations of the individual particle. The spans of the vector elements given in (20) are specified in Table 1. To compute the objective function ' η ' the custom built eigenvalue estimation program of the multimachine system as shown in Figure 2 runs for each particle. The values for the particle vector updates for each run and execution continues until reaches convergence. At the point of convergence PSO returns the best values of the controller variables and the objective function which are displayed in Table 1. The rate of minimization of the objective function towards optimal results for particle numbers 10 with generation size 150 is shown by the Figure 6. It has been noticed that the convergence is ensured about at generation step 40 and hold up to the last limit of the generation.

Table 1. Variables for STATCOM controller and PSO based results

Controller parameters	Typical span for the parameters (Low : High)	PSO generated value	ODI (η)
K_p	(0.1 : 10.0)	8.5329	0.5679
K_I	(0.1 : 2.00)	1.0211	
T_1	(0.1 : 1.50)	0.7682	
T_2	(0.01 : 0.25)	0.0100	

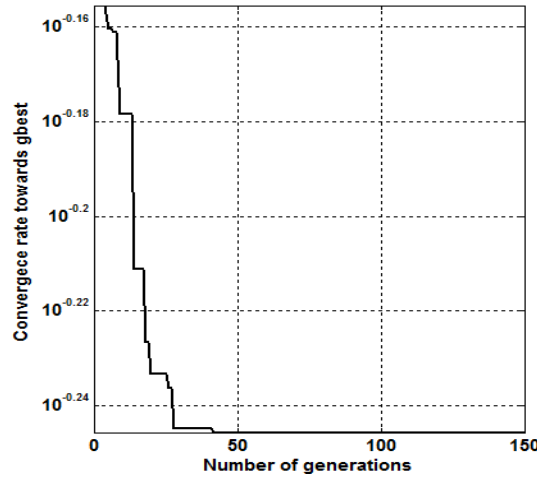


Figure 6. Minimization rate of the desired objective function

3.6. Digital STATCOM controller

The SPMU based voltage phasors measured from different substations are digital signals which are unable to process by the analog controller as shown in Figure 5. Again the direct design of higher order digital controller for a multimachine system is quite complicated. Therefore the PSO based continuous-time analog controller is converted to digital one via bi-linear (Tustin's) transformation. Hence if “s” is substituted by the term:

$$s = \frac{2}{\tau} \frac{1 - z^{-1}}{1 + z^{-1}}$$

In the continuous-time controller model shown in Figure 5, the resulting controller will be the digital controller. The schematic layout for the discrete-time STATCOM controller is depicted in Figure 7. The controller receives DSP based outputs, $V_{meas}(k)$ from different SPMUs installed with the generator buses. The controller generates control action signal $V_{sc}(k)$ which has to be processed further through “ZOH” before implementation to a continuous-time study power system.

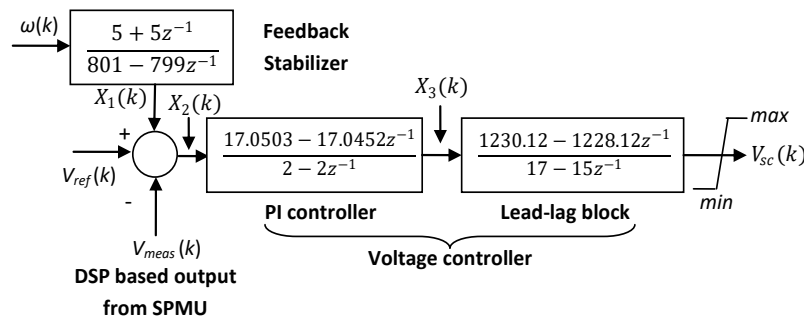


Figure 7. Digital STATCOM controller

3. PERFORMANCE EVALUATION

In this section performance of both the analog and digital controllers are investigated for a step change in machine speed deviation. The step response and time-dependent synthesis of the system are performed in MATLAB environment. The rotor speed deviation response of generator #1, generator #2 and generator #3 are calculated and plotted separately in Figures 8(a), 8(b) and 8(c) respectively for an analysis time 7 sec. It has been found that performances of both the controllers are satisfactory and they are suitable for improvement of instability phenomenon of the power system. However, it appears that digital STATCOM controller is capable to induce major damping in the speed deviation response and can bring the system quickly to the steady state condition against transient disturbances.

Figure 8 also clearly indicating the facts that peak overshoots and the settling time is substantially improved in each study case with application of the digital controller compared to the case of continuous-time controller. It has been further observed that both the controller imparted better response in generator #3 compared to the response observed in generator #1 and generator #2. In the response of generator #3 it is noticeable that overshoots and undershoots are occurring less in numbers and the system also reaches quickly to the steady state condition within 3 sec. Therefore, from the simulation results presented in Figure 8, it is viable to suggest that the digital STATCOM controller is more effectual in respect to the continuous-time analog controller in mitigating dynamic instability problems in a power system.

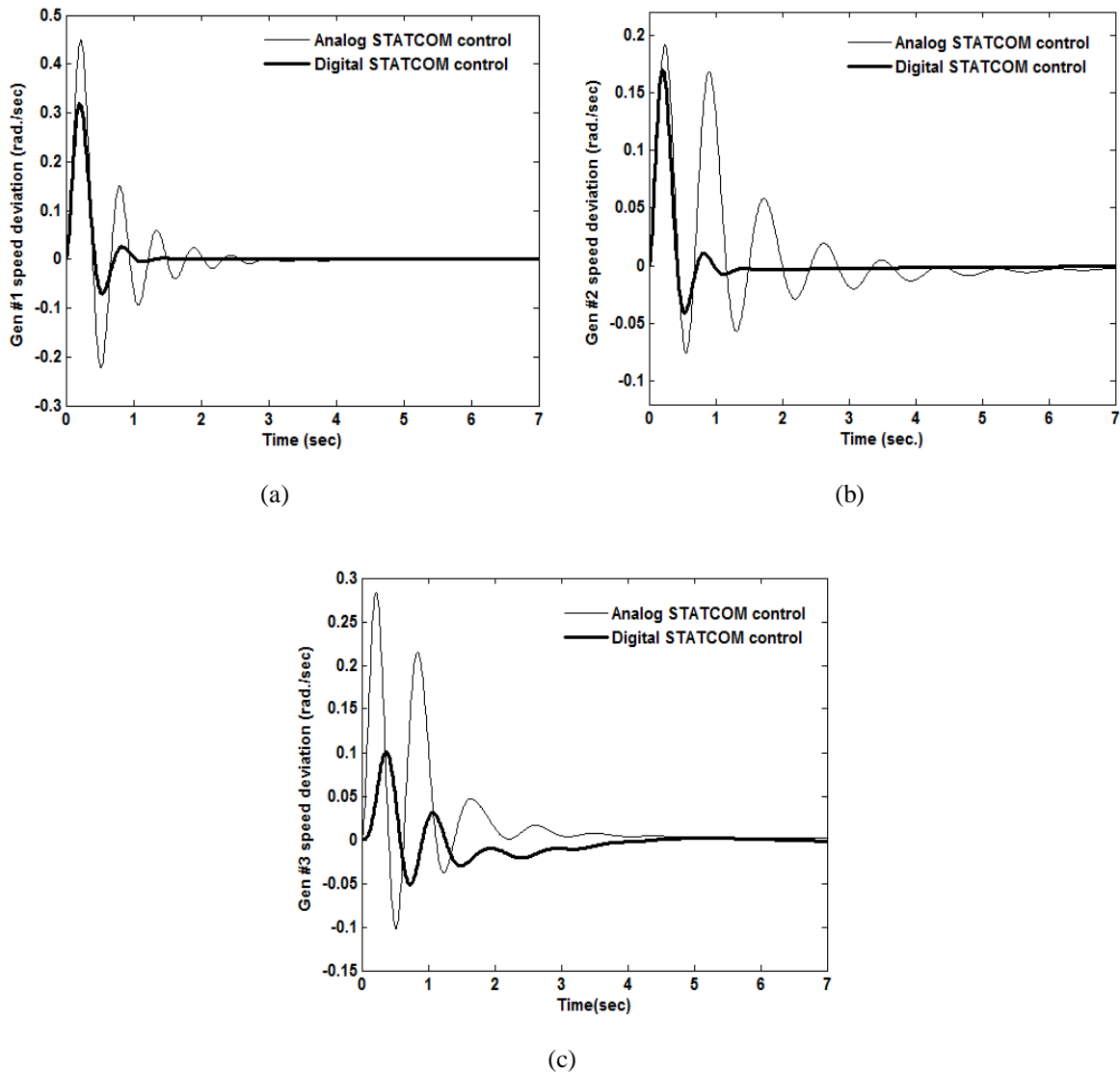


Figure 8. Dynamic profile of generator speed response, (a) generator #1, (b) generator #2, (c) generator #3

4. CONCLUSION

In this work the idea of synchronizing phasor measurement and its utilization for power system stability enhancement has been described. The PMU are strategically placed in a multimachine power system in decentralize manner. A PI type lead-lag STATCOM controller along with SPM unit is employed to inquire the dynamic instability problem of a multimachine power system. The analog model for the STATCOM controller is optimized by the PSO based optimization method. As the discrete time signal obtained from phasor measurement unit is unsuitable for processing by the analog controller, it is then converted to digital one with the help of Tustin's transformation. The intension of Tustin's transformation in digital control design is that direct design of digital control is a trivial task and the processing of infinite samples of impulse

response is practically not possible. Another objective of the author is to examine the performance of the digital control and the analog control for the particular task of interest in the manuscript. It has been established that the digital control set-up is substantially successful and superior than the analog control. The relevancy of the application of PMU is that implementation of DSP based control in wide area monitoring (WAM) for a multi area power system network. It is to be noted that the limitation of the wide area control like signal latency or transmission delay is not considered here by the author. The present work can be extended further considering signal transmission delay. The proposed plan can also be adopted considering different FACTS controller for some other multimachine power systems.

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